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LA-UR -87-3313

CONF-8710125--2

LA-UR--87-3313

DE88 000479

TITLE AN ADVANCED HADRON FACILITY: PROSPECTS AND APPLICABILITY TO ANTIPROTON PRODUCTION

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SUBMITTED TO PROCEEDINGS OF RAND WORKSHOP ON ANTIPROTON SCIENCE AND TECHNOOOGY, OCTOBER 6-9, 1987, Rand Corporation, Santa Monica, CA

MASTER

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AN ADVANCED HADRON FACILITY: PROSPECTS AND APPLICABILITY TO ANTIPROTON PRODUCTION

by

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ABSTRACT

An Advanced Hadron Facility is designed to address physics problems within and beyond the Standard Model. High fluxes of secondary beams are needed for the requisite precision tests and searches for very rare decay modes of mesons and baryons. Such high fluxes at useful secondary energies are readily obtained from high intensity, intermediate energy proton beams, which are also well suited to antiproton production. If the AHF primary proton beam were merely dumped into a beam stop, it would produce on the order of 10^{19} to 10^{20} antiprotons per operating year. Current collection techniques are not likely to be capable of absorbing more than one part in 10^{3} of this production. Thus, an AHF provides both the immediate possibility of collecting quantities of antiprotons substantially beyond those available from the LEF discussed at this meeting, and for significant increases in the available antiproton supply upon the development (at an AHF) of more efficient collection methods. The prospects are presently good for the completion of an AHF in the late 1990's.

I. INTRODUCTION

An Advanced Hadron Facility is needed to further precision tests of the standard model and to address problems both within it, and that go beyond its limitations. Nuclear physicists are primarily interested in the opportunities afforded to extend the study of QCD, the theory of the strong interactions, to longer distance (>1 fm.) regimes and in the nuclear medium. This effort is to be complemented by electron scattering experiments at Bates Laboratory and at the Continuous Electron Beam Accelerator Facility (CEBAF), and by heavy ion collisions to study the quark-gluon plasma using the proposed Relativistic Heavy Ion Collider (RHIC) at Brookhaven. Particle physicists are more concerned with experiments involving the electroweak interactions; these either provide precision tests of the standard model or search for new processes which illuminate questions not addressed within it. An introductory discussion of the standard model and a description of some of its problems and tests may be found in a companion paper available at this meeting. Here, I will only briefly review some of the most outstanding experiments which define the physics requirements for an AHF.

1.1 Electroweak Experiments

The most outstanding particle physics experiment at an AHF is the search for the decay of a neutral kaon into a muon and an electron. This process does not occur in the standard model unless neutrinos have non-zero masses. From the limits on those masses, the branching ratio for this process relative to normal kaon decay would be less than 10^{-30} at best. The present experimental limit is less than 10^{-8} and there is an experiment currently underway at Brookhaven to reduce this by at least one and possibly three more orders of magnitude. This limit may be interpreted as requiring the mass of a "family-changing" boson to be greater than about 30 TeV/c^2 (see Standard Model paper). Note that this is already beyond the range of new physics directly accessible at the proposed Superconducting Super Collider. At an AHF, the increased kaon flux, and beam quality allow this process to be searched for down to a branching ratio at the 10^{-13} level, which corresponds to a 500 TeV/c^2 mass. Once again, the value of a precision experiment is apparent. Although this limit is important, it would of course be even more valuable to discover the process and to be able to study it in detail. Thus, discovery of the process at a larger branching ratio would only enhance the value of an AHF which would provide the means for such study.

Within the standard model, the decay of a charged kaon to a charged pion and two neutrinos is not allowed to lowest order in the weak interaction, but does occur to second order by means of a quantum field theory correction. This process is sensitive to the number of light (mass much less than a kaon) neutrinos, and to details of the quantum field theory corrections. Because of uncertainty in these details, this process is only predicted to occur somewhere in the range between 10^{-10} and 10^{-11} in branching ratio. The current limit is at the 10^{-7} level. An AHF allows the observation of this predicted process and, again, detailed study of the new physics implied if the process is discovered at a larger branching ratio.

Studies of neutral kaon decays are also necessary to elucidate the physical basis for the observed violation of CP-invariance (the combination of charge conjugation, or exchanging particles and antiparticles, and of parity, or mirror reflection). Finally, there are neutrino scattering processes of interest with scattering cross sections as small as 10^{-41} cm^2, or about 15 orders of magnitude smaller than normally found for the strong interactions. As for the high precision or small branching ratio kaon experiments, these require enormous neutrino fluxes to be available if the experimental detectors are to be of reasonable size and cost. (Producing more kaons in the same volume -- higher brightness --

also obviates the need for larger and more expensive detectors for the work with kaons, too.)

Although some of these kaon experiments are best performed with stopping kaon beams (of momentum less than 1 GeV/c), many require high momentum beams (5-20 GeV/c). This is primarily due to the fact that the decay products are then also at high momentum, and are relatively less disturbed by the material in the detectors which analyze them. When the beam must be purified and momentum analyzed, relativistic time dilatation also helps reduce the contamination due to other particles (especially decay products) and minimizes the loss of kaon flux during that process. Studies at Los Alamos suggest that a 45 GeV/c primary proton beam produces sufficient quantities of these high momentum kaons. For most of the nuclear or strong interaction studies described next, lower momentum kaons would be preferable. However, more of those are also produced by a higher energy proton primary, and there is one particular experiment that demands an even higher energy proton beam.

1.2 Hypernuclear and Other Strong Interaction Experiments

Secondary beams of pions and kaons at an AHF would provide for a broader examination of the spectrum of strongly interacting states than has been made so far using only nucleon and pion beams. Despite decades of effort, the full spectrum of three-quark and of quark-antiquark states has not been experimentally observed. And with the advent of QCD, new exotic states containing extra quark-antiquark pairs or gluons, and states composed solely of gluons, have been predicted. Discovery and detailed study of these states is vital to our deepening understanding of QCD. Dibaryons, especially those containing more than one strange quark, and which are most easily and cleanly formed for better study using kaon beams, may be the first examples of new kinds of hadronic matter intermediate between nuclei and the quark-gluon plasma sought in heavy ion collisions.

Hypernuclei, containing one or more strange quarks, provide an extension along these lines which offers further opportunities to understand the relation between a QCD-inspired quark view of nuclear structure and the more traditional meson-baryon picture. Even in purely traditional terms, continuum states in ordinary nuclei can be shifted into the bound state spectrum of corresponding hypernuclei, allowing for more detailed study and verification of our understanding of the forces in non-strange nuclei. Lower momentum (0.5-2.0 GeV/c) kaon beams are very efficient at producing these hypernuclei by strangeness exchange, as the momentum transfer can be minimized with excess energy being carried off by an outgoing pion; this leaves the resulting hypernucleus in a very low excitation (if not the ground) state.

Due to their relatively small cross-section even at low energies, positively charged kaons also make an excellent probe of the matter distribution of ordinary nuclei in elastic and quasi-elastic scattering. The distortion corrections so difficult to apply for pions are significantly reduced, making the connection between theory and experiment more direct and transparent. Through the so-called Drell-Yan process, however, a higher energy proton primary may provide even more significant information on the (nuclear) medium-induced distortion of the nucleon structure itself.

In the Drell-Yan process, a quark and an antiquark from the beam and target annihilate to form a off-shell photon, which immediately "decays" into a muon and and antimuon, or into an electron and positron. It is particularly easy to identify these particles and to measure their momenta. From the kinematics of this final state pair (overall mass and momentum), one can infer the momenta of the initial quark and antiquark involved in the (sub-)scattering. For a 60 GeV/c proton beam, it turns out that the kinematic region is large enough to allow a detailed study of the antiquark probability distribution in the (nuclear) target. (The quark distribution in the incident proton is well-known from high energy, deep-inelastic electron scattering on hydrogen targets.) From electron scattering experiments on nuclei, it is known that this scattering, even at high energy, cannot simply be represented as a sum of incoherent scatterings on the individual nucleons (isolated in space), a result termed the EMC effect after the European Muon Collaboration which made the experimental discovery. This effect can be described as due to a distortion of the nucleon structure by the nuclear medium. However, experiments have not so far resolved whether this is due to a change of the three-quark structure of the bound nucleon, or due to the formation of additional quark-antiquark pairs (perhaps even correlated into pions). This Drell-Yan experiment offers the cleanest possible test of these conjectures. Such an understanding of the nucleon structure within the nuclear medium is crucial to a QCD-based understanding of nuclear structure, and is an extremely interesting and important question for nuclear physics.

2. PRIMARY AND SECONDARY BEAM REQUIREMENTS

This broad range of exciting physics clearly demands a broad range of primary and secondary beams and beam momenta. Low momentum beams are particularly demanded by hypernuclear studies and "stopped" decays. Low to intermediate momenta are required for meson and baryon spectroscopic studies and for in-flight decays. Finally, the highest momenta are required for Drell-Yan studies of the EMC effect. It turns out that these requirements are not mutually conflicting due to general properties of particle production for secondary beams.

As shown schematically in Fig. 1a, the cost of an accelerator complex such as the AHF is roughly proportional to the total beam power. Thus, at constant cost, one may increase the primary energy only by reducing the beam current. Because the phase space constraints on the number of particles per "bucket" of the radiofrequency accelerating voltages are most severe at the lowest (injection) energy for each step, it is somewhat easier to design a system at lower current. One is then naturally driven to higher energy, lower current machines. However, as shown in Fig. 1b, both the mean momentum and the flux of secondaries in each momentum bin rises with increasing primary energy; the low momentum secondaries are a smaller fraction, but of a larger total. Thus, one can obtain the desired range from low to high momentum secondaries without cost to the lower momentum flux.

This provides a natural benefit for production of antiprotons which are ultimately desired at low energies. Antiproton production has a similar structure to that shown for any secondary. There is a "knee", or decline in the rate of increase of production, which occurs for a proton primary in the region of 40 to 80 GeV, and a continued increase in the mean antiproton momentum produced. Thus, while total production continues to rise, if these antiprotons are to be deaccelerated after being captured, this will become increasingly difficult and expensive. So fortunately, the general physics demands for an AHF place its primary beam energy in an excellent region for efficient production, collection and deacceleration of antiprotons.

3. SURVEY OF AHF PROPOSALS: THE GENERIC AHF

There have been six areas of the world in which there have been discussions relevant to an AHF. The Japanese are embarked on upgrading the current and energy capabilities of the proton synchrotron at KEK. However, even at 12 GeV energy and 10 μA current, this is insufficient to be a true "kaon factory". In the Soviet Union, there has been some consideration of an AHF near Moscow, and in Western Europe, there has been a conference/workshop regarding a European Hadron Facility. The sponsoring group of the latter, however, is not associated with any particular laboratory, which may prove a significant drawback to realizing their plans. There have been detailed discussions at Brookhaven regarding increasing the 30 GeV machine current there up to 10 μA. Unfortunately, an AHF is competitive for machine time with RHIC, which is the stated highest priority of that laboratory. The two most serious efforts have been at the Canadian pion factory, TRIUMF, in Vancouver, and at LAMPF, in Los Alamos. The Canadian KAON (Kaons, Antiprotons, Other hadron and Neutrinos) proposal is for a 30 GeV, 100 μA machine, which represents an effective, if relatively low energy, AHF.

The Los Alamos AHF proposal has been through a number of variations in response to efforts to maximize the efficacy of the machine for research in several additional areas (including pulsed muon and neutron beams for material science studies) and to minimize costs in response to budgetary constraints. The original proposal included a 6 GeV booster designed to provide maximum current for a neutrino source, and a 45 GeV main ring, capable of up to 68 μA average current. Since then, various options considered have included LINAC boosters of up to 2 GeV of kinetic energy, and a coupled 15 and 60 GeV booster and main ring with a 50 μA current. These energy and current trade-offs reflect the design constraints referred to earlier. (See Fig. 2 for a Los Alamos version of an AHF.)

From the panoply of these proposals and designs, a common theme emerges for a generic AHF: It has a low energy injector, most often a LINAC, which drives a maximum amount of current from a few kiloVolt ion source up to relativistic velocities on the order of 85% of the speed of light. Next comes a booster, which bridges the transition to the fully relativistic regime (99% of the speed of light). This requires the widest range of change in radiofrequency of the accelerating fields, and hence is the most difficult to achieve. Typically, this booster cannot make use of all of the current that can be supplied to it. Next comes a final or main ring which again cannot absorb all of the current supplied. It raises the beam to the final energy of 30 to 60 or more GeV, using only a modest swing in the radiofrequency of the voltage applied to the accelerating cavities. In between these stages may be compressor rings to collect pulses from the lower energy device and manipulate them to enhance the current which can be accepted into the higher energy device. At any stage, but especially at the highest energy, a stretcher ring may be added to smooth out the extracted current and provide a better duty factor for experiments.

4. THE PRODUCTION OF SECONDARY BEAMS AND OF ANTIPROTONS

There is no reason to suppose that any less efficient use of the primary beam can be made for secondary particle production at an AHF than at lower current accelerators. And, in fact, antiprotons are even a significant contaminant in kaon beam designs. (See Fig. 3.) But just to set the overall scale for antiproton production, let us consider what would occur if the proton beam were simply passed to the beam dump, without encountering any production targets. In a dump, the protons all interact, usually more than once although at rapidly declining energies. Interpolation formulae based on some production measurements (see Hojvat and van Ginneken) suggest that at 60 GeV, about one antiproton is created for every 100 proton interactions. Therefore, in the dump, the 3×10^{14} protons per sec of AHF primary produce more than 3×10^{12} antiprotons per sec. As there are typically 10^7 operating seconds per calendar year at such a research facility, we see that the total production exceeds 10^{19} and may approach 10^{20} antiprotons per year.

Explicitly, the formation of secondary beams at an AHF is shown schematically in Fig. 4. Following the example of LAMPF, the extracted beam is sequentially transported to a sequence of production targets, each of one interaction length or less. This is a compromise between getting the primary protons to interact, and getting the secondaries out of the target without excessive absorption losses. A short target also reduces optics problems in the secondary beam lines. With appropriate design, both neutral and charged (either sign) secondaries may be derived from any target station. Since a sizeable fraction of the scattering is elastic or quasi-elastic, there is still significant beam power at the dump, although it is relatively diffuse. (See Figs. 5 and 6 for typical target and target station/secondary beam extraction line designs.)

One of the problems of targetry is the power dissipation level in the production targets. LAMPF has considerable experience with targets involving beam powers only a factor of 3 to 5 lower than the ~1 MW total anticipated for an AHF. Thus, while difficulties, even severe ones, are to be expected, insurmountable problems are not. One of the advantages of a higher current machine over one at higher energy shows up here: phase space limitations require that the current be raised by increasing the frequency of accelerating "buckets" with the same number of particles per bucket. (These buckets are 25% full in the conservative designs originating from Los Alamos.) Thus, the thermal shocks to the target are increased in frequency, rather than in magnitude, and the problem can be limited to one more of cooling rate than of structural damage, as has been found in the production targets at Fermilab and at CERN.

The peak instantaneous target loading at the Los Alamos AHF is of order 5×10^{13} protons over 4 μsec at up to 60 GeV, compared to a similar number at CERN delivered over half the time interval at about half the energy. The Fermilab current is an order of magnitude smaller than at CERN, but at up to six times the proton energy. These currents deposit a great deal of energy "instanteously" in the beam spot region, and heat this region to within a factor of two of melting temperatures, for the typical W or Cu targets used. Nonetheless, the average target temperature can be well below 1000°C.

The beam-induced shock tends to crack and powder high yield strength materials such as W. (A strong cladding, such as Ti, is provided to maintain structural integrity. Using a lower stength material with a larger range of acceptable plastic yield, such as Cu, results in voids (presumably from gas produced in the target) over periods on the order of months. Both of these effects reduce target density and so antiproton yield. Thus, the higher currents at an AHF raise serious questions regarding useful target lifetimes (greater than a day?). At present, target design is inhibited by a lack of knowledge regarding the equation of state of materials under high stree in the plastic deformation region. Los Alamos is in a position to remedy this, as our M-Division presently pursues just such studies for nuclear materials, among others, using high-explosive driven shocks.

There may be interesting possibilities to study in the area of throwaway targets, such a liquids, or moving wires or ribbons[1], (both of which require containing highly radioactive wastes), as well as beam-on-target management techniques such as "painting" Lissajous patterns, while similarly adjusting the collector acceptance, or focusing the beam into a ribbon structure. (Beam-sweeping techniques are sure to work, but may be very expensive.) As a last resort, target lengths (currently 5-10 cm) can be shortened, and the number increased. This reduces the load faster than the length is reduced as electromagnetic energy can escape more efficiently before the showers are fully developed. (Again, depth-of-field problems in the secondary beam-line optics are also ameliorated.) One is limited in doing this in the transverse direction by the requirement that the difference δ, between target and beam sizes satisfy

$$\delta > \nu t \qquad (1)$$

where ν is the speed of sound in the target and t is the pulse length of the incident beam.

The peak power on target at CERN is currently 2-3 times that of Fermilab, and another similar factor of increase can be reasonably forseen, even without sweeping, etc. techniques. Similarly, the total energy deposition is approaching, (at least with Cu targets), but has not reached the nominal 200 J/gm limit. Thus, it seems quite likely

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1 Krienen and Mills have suggested that there are advantages to moving the target material at greater than the shock velocity.

that targets will not limit antiproton production at an AHF. The biggest question for the long term, however, is whether target design can help improve collection efficiencies. At present, Lithium lenses are used to focus the antiprotons onto the acceptance of a collector. Can these cycle faster? And can their focusing be improved by integration with the target? Unfortunately, this will increase the target heating significantly.

5. COLLECTION AND COOLING

What would it take to collect an appreciable fraction of the enormous available production? Note first that the sequential target design of an AHF naturally means that even a target station dedicated to studying this question would not significantly interfere with the main scientific goals of the AHF. At any point, collectors/decelerators followed by coolers and "bottlers" could be added (see Fig. 7), perhaps even at the beam dump itself. The second thing to notice about collecting and cooling the antiprotons produced at an AHF is that the secondary flux is still negligible in beam current. The product of the production and collection efficiencies is such that less than one antiproton appears in the collector for every $10^{5\pm1}$ primary protons. Thus, one does not have to worry about any beam loading type problems -- only the wretched phase space occupied by the antiproton secondaries: The size and scale of current collectors is adequate to absorb a significantly larger number of antiprotons.

Thirdly, notice that the antiproton source brightness is about two orders of magnitude greater at an AHF than at Fermilab, one from the number of particles per bucket and one from the increased cycling rate. Thus, whatever lenses/collection efficiences are available, now or in the future, an AHF would seem to guarantee an immediate factor of 100 improvement in the number collected. Actually, there is only one caveat here. The best Fermilab collector design makes use of a phase space rotation to accept a large momentum bite of antiprotons and convert it to a small width momentum distribution in the collector. To make use of the increased brightness, this procedure must also be capable of cycling ten times faster.

Of course, in the future, one would also like to increase the collection efficiency. This requires larger acceptances in the transverse and longitudinal antiproton momenta. Fig. 8 shows the longitudinal momentum spectrum of antiprotons produced by 45, 60 and 80 GeV protons on a tungsten target, calculated using formulae fit to actual production data. (See again the work of Hojvat and Van Ginneken.) It is distressingly wide, and the effort at Fermilab has already been very clever about making maximum use of it. However, there is still an order of magnitude to be had. Will it be by clever lens design? Is it even possible to use this additional flux unimaginatively by directing the rings of incompletely focused higher momentum antiprotons into parallel collectors?

On the other hand, the transverse momentum distribution has a 1 GeV/c scale, as might be expected from dimensional arguments in QCD. Thus, there is not a particularly wide angular spread of the antiprotons near the momentum peak. (This feature is worse at a lower energy AHF, such as the TRIUMF proposal.) As a result, increasing the angular aperture of collectors will not be very cost effective, although as much as a factor of five improvement may still be available over current designs. This is also related to the question of lens design since an appropriate angularly dependent chromatic aberration can add at least high momentum particles into the region of acceptance.

Stuffing two to four orders of magnitude more of antiprotons into a collection system will do us no good, however, unless we can cool them at correspondingly higher rates. There does not seem to be much more (×10) rate available with currently employed stochastic cooling, due to bandwidth and frequency limitations. Stochastic cooling times (τ) are proportional to the number of particles (N) to be cooled and inversely proportional to the bandwidth (Δf) of the kicker/amplifier system:

$$\tau \propto \frac{N}{\Delta f} \qquad (2)$$

The amplifiers/bandwidths currently used are in the several GHz range. Thanks to radioastronomy, amplifiers up to 80 GHz already exist, but large bandwidths have yet to be demonstrated.

Even if tens of GHz bandwidths are achieved soon, this is just enough to make use of one factor of 10 increase in brightness of the antiproton source at an AHF. If the full brightness is realized, or if either of the additional two orders of magnitude of angular and longitudinal momentum collection efficiency available are realized, even higher frequencies will be required. Although such amplifiers appear quite plausible, here we do seem to run into a fundamental limitation, as wavelengths smaller than the beam size can be of no use. For typical mm beams sizes, this means a 1 THz limit or less, unless one can arrange to focus the beam to a smaller size in the pickup and kicker regions Thus, we must also consider other cooling mechanisms.

Antiprotons are too massive for significant radiation cooling, even at much higher magnetic fields (which may be achievable with the new high temperature superconductors, eventually). This leaves only electron and ionization cooling. The latter involves passing a widely dispersed antiproton beam through a material which absorbs energy by being ionized, and then re-accelerating the antiprotons to recover the longitudinal energy loss. In the EHF proposal, it is argued that this leads to unacceptably high annihilation losses while the antiprotons traverse the material. (This incidentally argues against the otherwise ingenious idea of D. Cline to solve the target, solid angle and cooling problems at one stroke by using colliding beams, a 4π solenoidal magnetic collecting field aligned with the beams, and a gas in the magnetic field volume to collisionally slow the antiprotons. This idea also faced a question of overall rate, due to the notoriously low luminosity of colliding beams.) This leaves us with the prospect of producing large currents of 3 to 4 MeV electron beams running parallel to the antiprotons, since their cooling effect is best at low relative velocities. Obviously, much innovative research remains to be done.

Lenses, collectors, coolers -- all of these features are clearly very expensive add-ons to the AHF, as it has so far only been envisaged to produce higher-energy antiprotons for research purposes. This has been partly due to the extra cost for collecting/cooling/decelerating, but also partly due to the perception that LEAR (and possibly Fermilab) would provide much of hte low-energy antiprotons needed for that research well before turn-on of the AHF. Thus, R&D for increasing the supply of low-energy antiprotons must be viewed as a significant additional cost at an AHF, even though it should cause only minimal interference with the basic research program.

It is difficult to seriously imagine today how to make use of the entirety of the antiproton production available at an AHF, other than by multiplexing targets, collectors and coolers. However, the cooling/collection rates achieved at Fermilab and at CERN are some four orders of magnitude smaller than needed. Given their scale of size and costs, the multiplexing of collectors and coolers is only an existence proof of little comfort and less imagination. On the other hand, this makes the AHF an attractive place to study the problem of increasing the collection: With the antiprotons right there for the taking, there is a powerful incentive for thinking up a good way to get them.

6. PROGRESS TOWARDS AN AHF

There has already been much progress on technical elements of an AHF, around the world. I will mention only two particular items developed at Los Alamos which I find particularly interesting.

The first of these is the beam pipe itself. The high beam current produces eddy current heating in a conducting beam pipe, in addition to the eddy-current magnetic field distortion due to the rapid-cycling magnetic fields. The Los Alamos solution (see Fig. 9) is a ceramic (alumina) beam pipe with transverse and longitudinal strips of metallization separated by insulating layers, and a thin, vapor deposited interior metal coating (≈ 1000 Angstroms of Ni). This reduces the eddv currents, while still providing low impedance paths to avoid the buildup of static charge and to provide for high-frequency image charges needed for beam stability.

The second is the nature of the accelerating cavitities in the intermediate booster. These require a wide tuning range because of the significant change in velocity, but also high efficiency to provide the power demanded by the heavy beam loading. These seemingly contradictory demands have been satisfied by changing the cavity tuning design from the standard parallel-biased ferrites (bias magnetic field parallel to the RF magnetic field) to a perpendicular bias design (see Fig. 10). Test cavities have demonstrated Q's in excess of 2000 over a 25% tuning range from 60 to 80 MHz, (see Fig. 11) which is more than sufficient. The cavity was tested to breakdown, which occured at 140 kV, well above the 80 kV design limit. It is apparent that every "kaon factory" built will use cavities of similar design.

On the political front, an AHF is beginning to get more attention, also. After some consultation with the community, the Nuclear Science Advisory Committee (NSAC) developed a long range plan (in 1983) calling for an intermediate energy high duty factor electron accelerator, which is embodied in CEBAF currently under construction, a high energy heavy ion collider, which is embodied by RHIC which is awaiting construction funds, and finally a kaon factory, or AHF. At a Washington luncheon this spring, D. Allan Bromley of Yale noted that with the first two elements of the plan falling into line, it was becoming time to seriously consider proposals for an AHF to be available in the late

1990's. (A new IUPAP committee has also been formed to consider the building of a kaon factory.) Indeed, the proposal from TRIUMF has already cleared several important hurdles in Canada, including lining up a significant fraction of the required funding. The remaining question seems to be whether Canada, a country which has traditionally funded science at a lower level than in the United States, wishes to undertake science funding at a level in their economy comparable that of the SSC here.

7. BEYOND THE AHF

Without any improvements in target engineering or in cooling rates, an AHF will do no better than Fermilab at producing antiprotons. However, it will be able to do so with a tiny fraction of its total current. If only cooling rates can be improved (as seems possible at least with electron cooling), then with Fermilab collection efficiencies an AHF could provide up to 10^{17} antiprotons per year. And over a ten or twenty year period, up to two orders of magnitude increase in the collection efficiency may be realizable. Thus, an AHF offers the prospect, over its research lifetime, of a total of four orders of magnitude increase in antiproton supply over that envisioned at the LEF. Can we imagine going even further?

I have noted that there is a serious problem in collecting and cooling antiprotons as well as producing them at large rates, but I believe these problems can can be solved when large, "hot" supplies are available on which to test out appropriate ideas. So the question becomes one of the intensity limits for intermediate energy accelerators of the primary protons. To go further in this area probably requires that we turn away from sychrotrons and return to linacs. These are intrinsically high current devices (10 mA?, 1A? -- even higher currents have been proposed at lower energies), heretofore limited by the cost of input power. For instance, with further improvements in superconducting accelerating cavities, a linac only an order of magnitude larger than

LAMPF ($\approx$1 km) could reach the appropriate energies for efficient antiproton production. With focusing quadrupoles interspersed between accelerating cavities, even higher currents should also be achievable. Thus, again apart from the questions of how to collect and cool them, we can already imagine, before an AHF, that successors to it could be built which would produce fractions of a gram per year of antiprotons.

8. CONCLUSION

An Advanced Hadron Facility has a strong science justification. There are also some scientific reasons for stretching its energy to the higher values more suitable for efficient antiproton production, collection and deceleration to rest. It will produce significantly large quantities of antiprotons per year, but significant expenditures will be required in add-ons to capture only a very small fraction of this production. New collection/cooling ideas are needed to fully utilize the output that will be available.

Nonetheless, the intermediate prospect is for tens of μg of antiprotons per year to become available at an AHF. Lest this strike you as fantastical, let me point out that significant amounts of antiparticles are already being produced and used for engineering convenience! For example, in the March 1987 issue of the CERN Courier, the 7 GeV Advanced Photon Source at Argonne National Lab was described. An earlier stored electron beam light source at Wisconsin (Aladin) had had significant difficulties maintaining long beam lifetimes due to positive ions from residual gas being attracted into the beam. Heroic efforts at cleaning the beam pipe and improving the vacuum were required to solve the problem. The group at Argonne found it more convenient to produce, collect, and store positrons, since in this case residual positive ions would be repelled from the stored beam. In some respects, the difference in problems is simply a matter of scale! And it will take some time to gain the factor of 2000 between electron-positron pair threshold and that for antiprotons. But perhaps it is indeed only a matter of time.

I am glad to thank R. D. Carlini, D. Grisham, and H. A. Thiessen of Los Alamos, and J. Dugan, J. Griffin, and J. Mariner of Fermilab for valuable conversations.

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Proceedings of the Workshop on Nuclear and Particle Physics at Energies Up to 31 GeV: New and Future Aspects, Los Alamos LA-8775-C (Jan. 1981), ed. by J. D. Bowman, L. S. Kisslinger and R. R. Silbar.

FIGURE CAPTIONS

Figure 1. a) Beam current vs. beam energy at constant beam power. Costs increase with increasing beam power. b) Flux of secondaries at fixed secondary momentum and (same curve) mean momentum of secondaries from a production target vs. beam energy.

Figure 2. A recent Los Alamos design for an Advanced Hadron Facility based on LAMPF as an injector.

Figure 3. Antiproton contamination in kaon beamlines at a 45 GeV AHF> These are rates rates at the end of the secondary beams for 24 μA of extracted proton beam, including absorption of both primaries and secondaries in the targets and decay in the secondary beam transport. Targets 1 and 2 are assumed to be 5 and 10 cm of tungsten, respectively. The dashed curves are for the available solid angle of the channel when separators are used and the solid curves are for the maximum solid angle without separators.

Figure 4. Schematic layout of production targets and secondary beams at a generic AHF. Magnetic separation of charged secondary beams is indicated at each target station, as are beam focusing quadrupoles between stations.

Figure 5. Possible design for rotating production target for an AHF.

Figure 6. Typical target station/secondary beam extraction design at an AHF. Extraction from a) target 1 and b) target 2): Q - quadrupole, HQ - half-quadrupole, Q8 - narrow quadrupole, BH - H-type bending magnet, BWF - window frame-type bending magnet, 6P - sextupole.

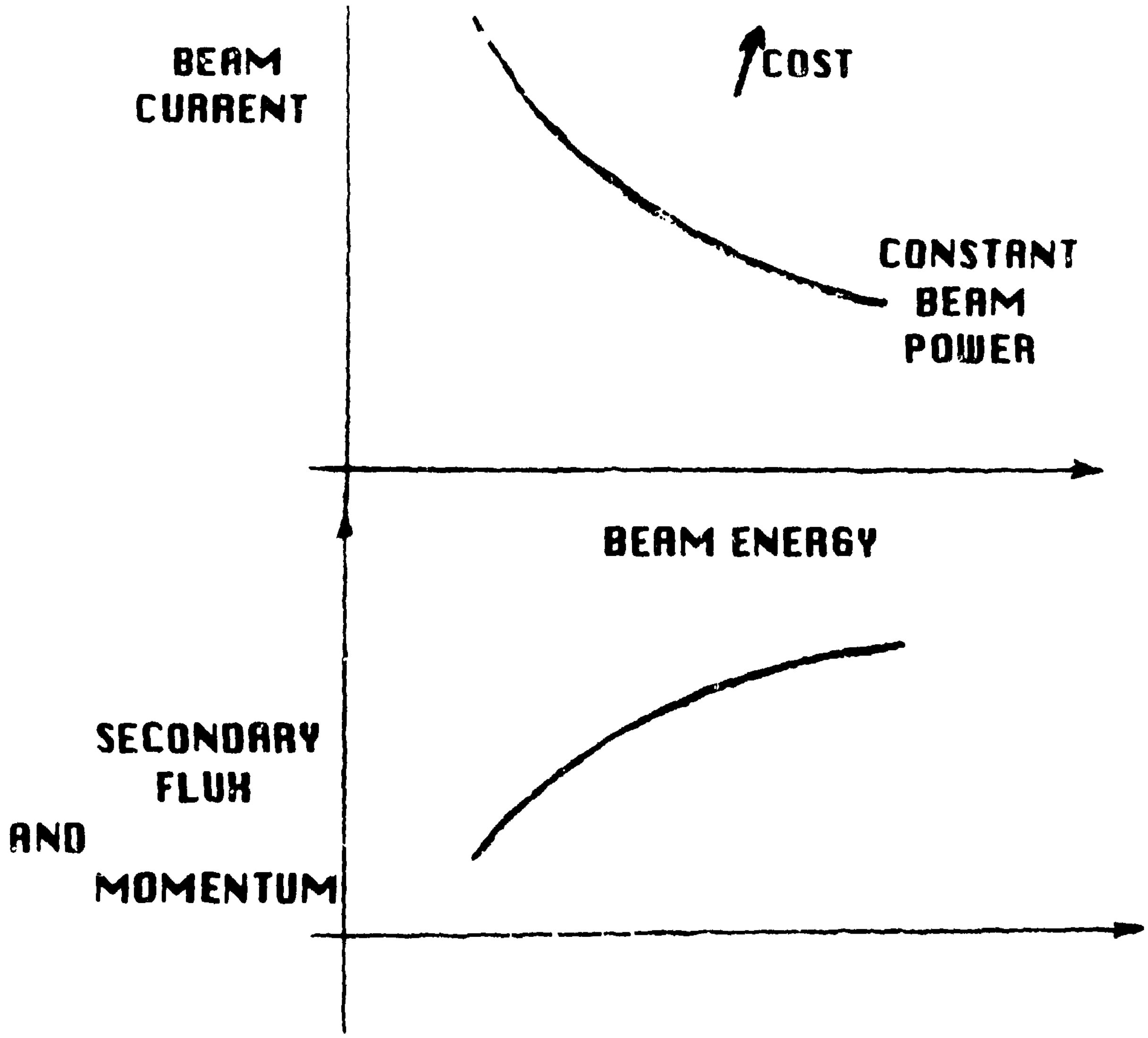
Figure 7. Antiproton collector/cooler test designs could be added to an AHF at any production target, or a dedicated target station could be used, both without interfering with other research.

Figure 8. Differential cross section for antiproton production on tungsten vs. produced antiproton momentum at zero degrees per differential unit (DW) of solid angle: a) On log scale at 60 GeV primary proton energy. b) On linear scale at 60 GeV primary proton energy. c) On log scale at 45 GeV primary proton energy. d) On log scale at 80 GeV primary proton energy.

Figure 9. Construction of eddy-current resistant vacuum beam pipe for proposed Los Alamos AHF.

Figure 10. Los Alamos d[illegible] perpendicularly biased RF accelerating structures for an AHF. [illegible] for the power tetrode region, the structure is a figure of revolution about the beam axis.

Figure 11. The variation of a test cavity Q with frequency. The upper curve (Q_r) is the calculated Q of the cavity, assuming that the ferrite samples are lossless and that the only loss is due to the resistivity of the metal cavity walls. The two G26 curves were obtained with type G26 Mg-Mn-Al ferrite toroids manufactured by TDK. The upper curve was obtained with perpendicular bias applied to the ferrite, while the lower curve shows the cavity Q when it is tuned in the conventional manner with parallel bias. The Y1 curve was obtained with type Y1 aluminum-doped yttrium-iron-garnet ferrite (also manufactured by TDK Electronics Co., Ltd).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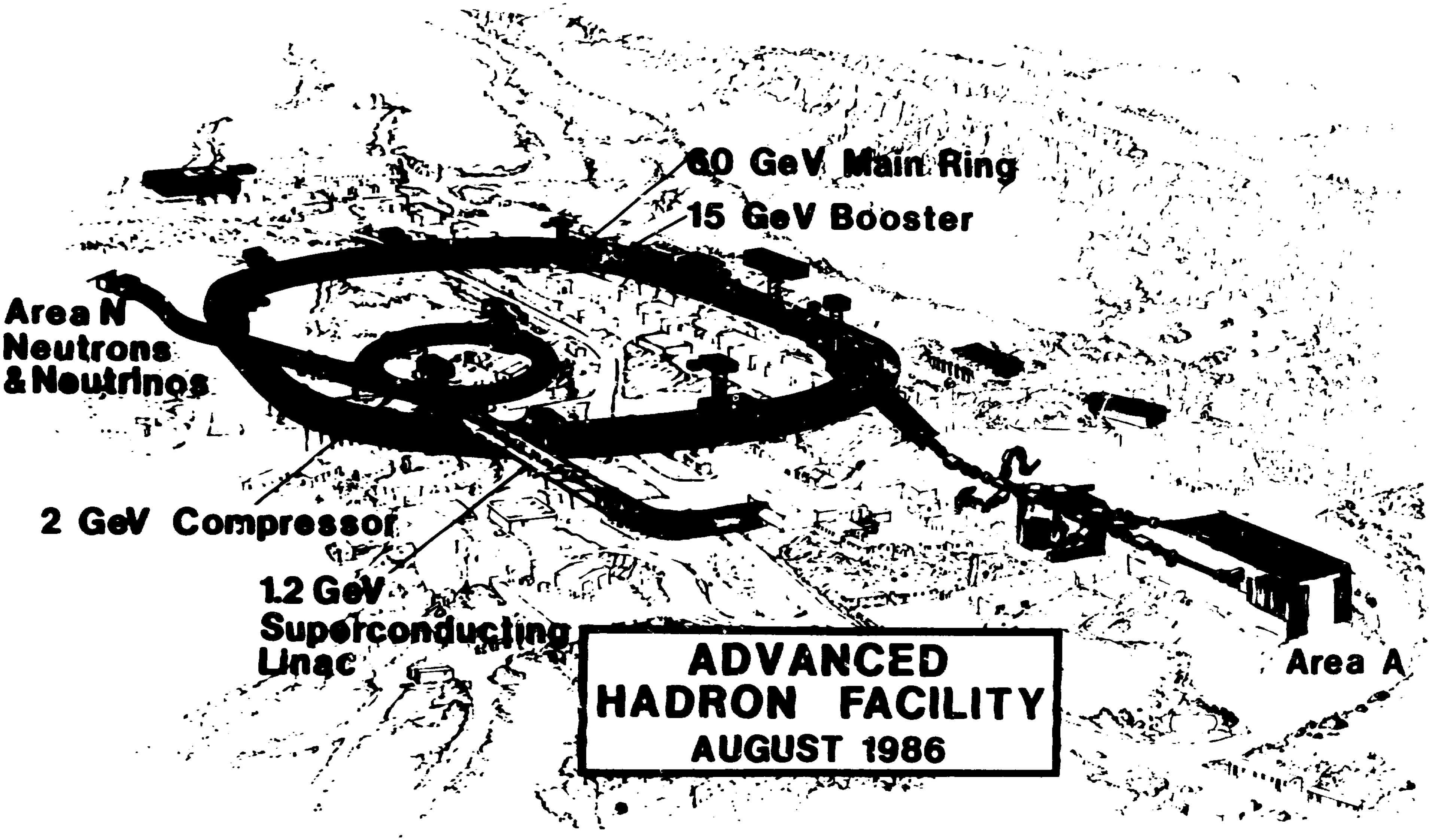
COST
CONSTANT BEAM POWER
BEAM ENERGY
SECONDARY FLUX AND MOMENTUM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15 GeV Booster
Area N
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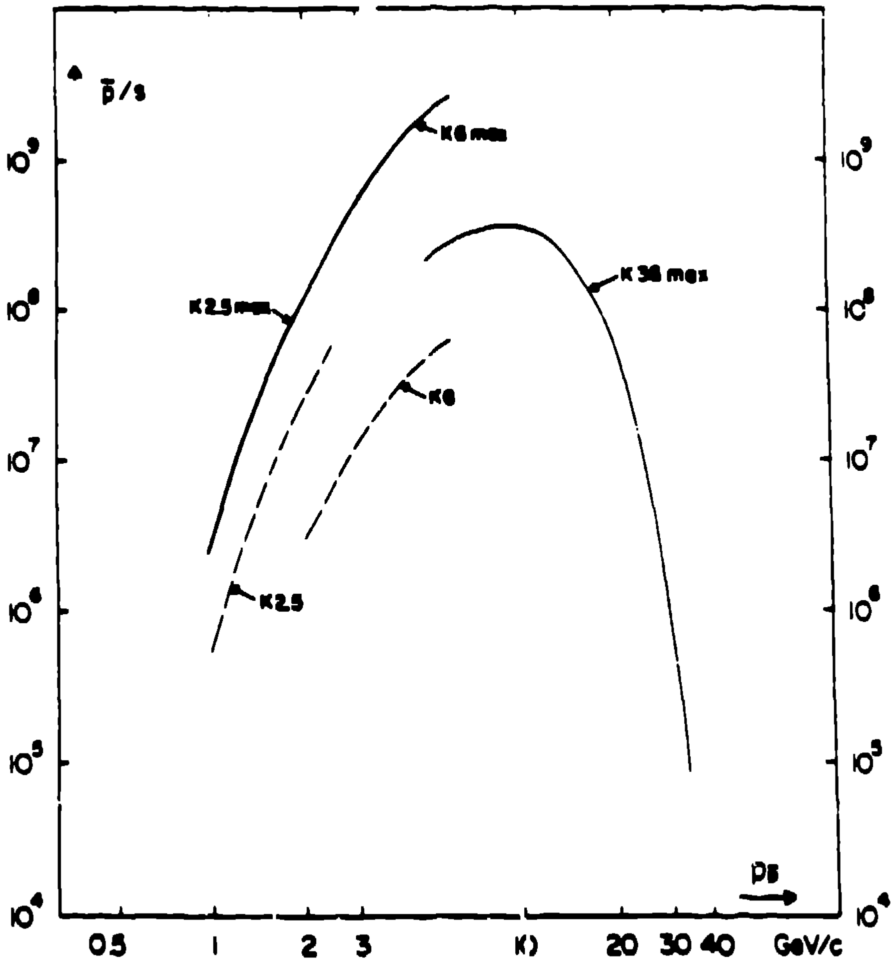
& Neutrinos
2 GeV Compressor
1.2 GeV
Superconducting
Linac
ADVANCED
HADRON FACILITY
AUGUST 1986
Area A



p̄/s
K6 max
K2.5 max
K38 max
K6
K2.5
10^9
10^8
10^7
10^6
10^5
10^4
$p_{\bar{p}}$
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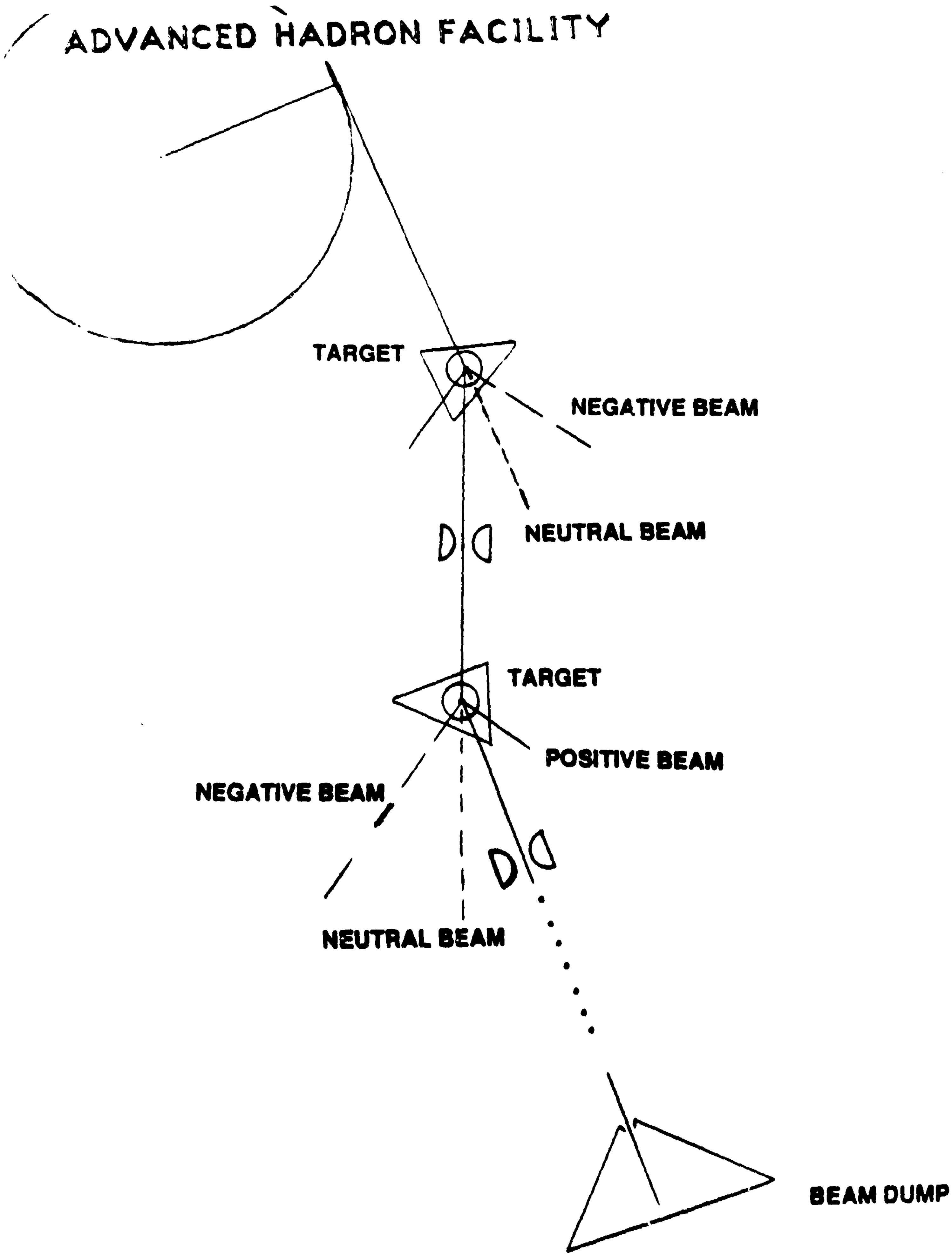
1
2
3
10
20
30
40
GeV/c


ADVANCED HADRON FACILITY
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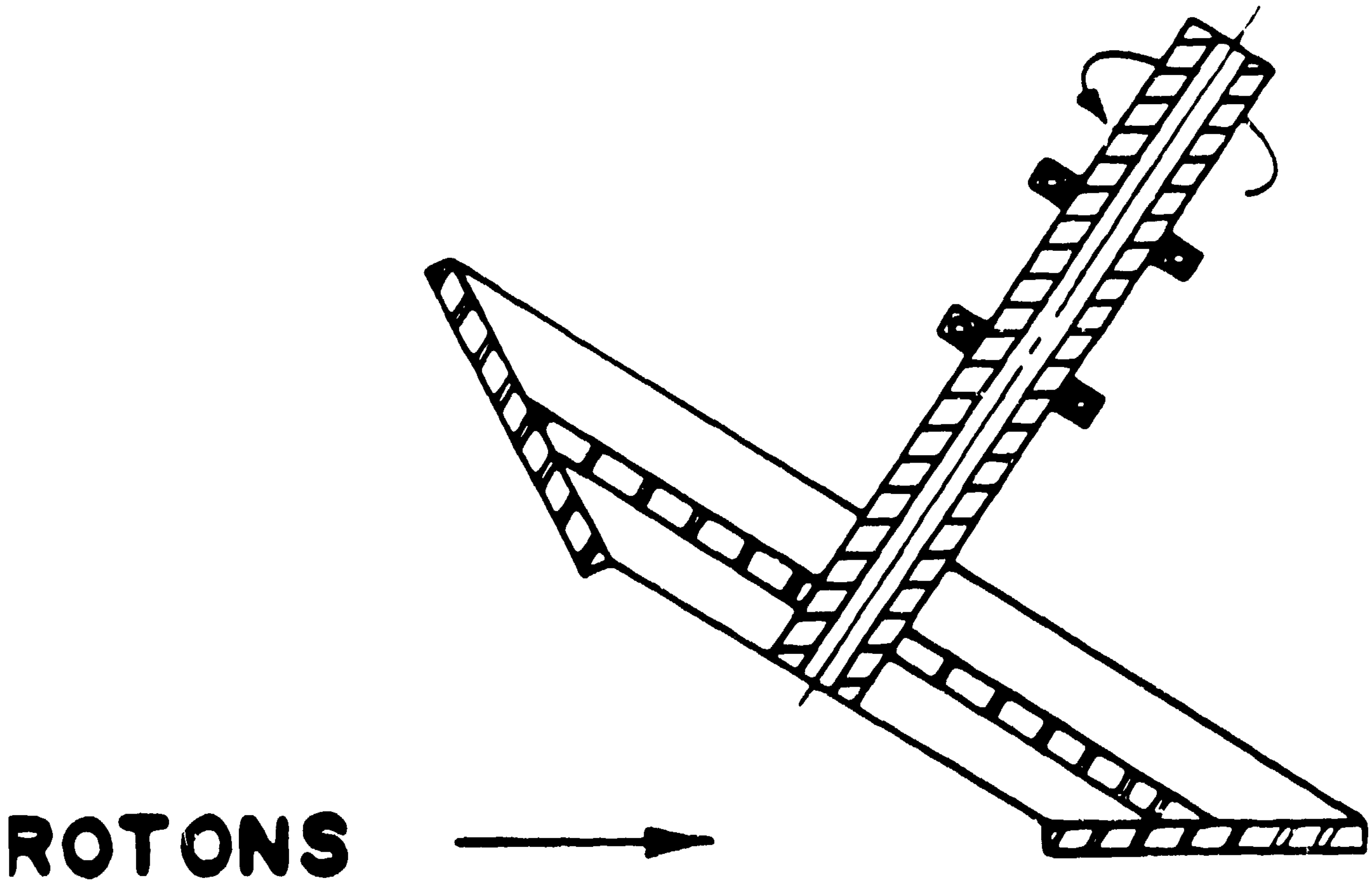
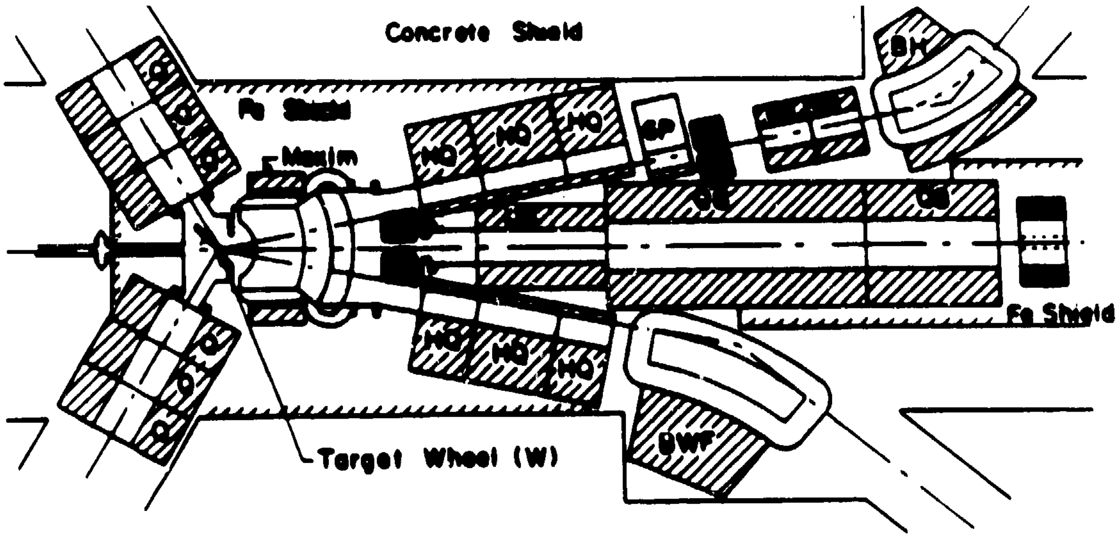
NEUTRAL BEAM
TARGET
POSITIVE BEAM
NEGATIVE BEAM
NEUTRAL BEAM
BEAM DUMP


ROTONS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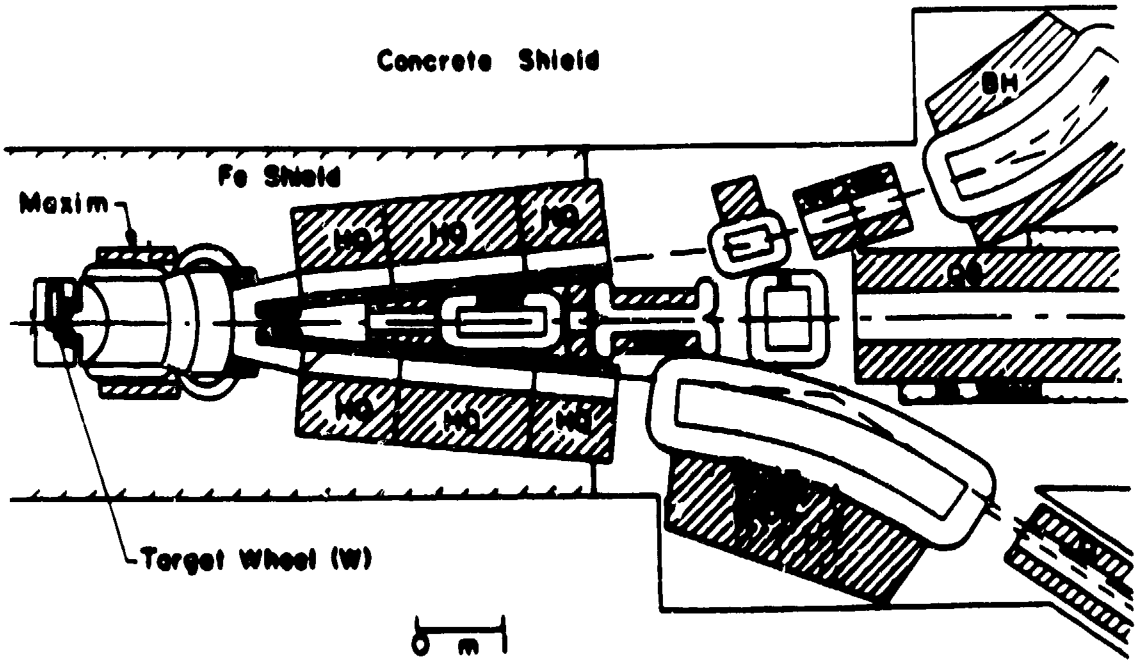
Fe Shield
Maxim
HQ
HQ
HQ
HQ
HQ
HQ
BH
Q
Fe Shield
BWF
Target Wheel (W)

(a)


Concrete Shield
Fe Shield
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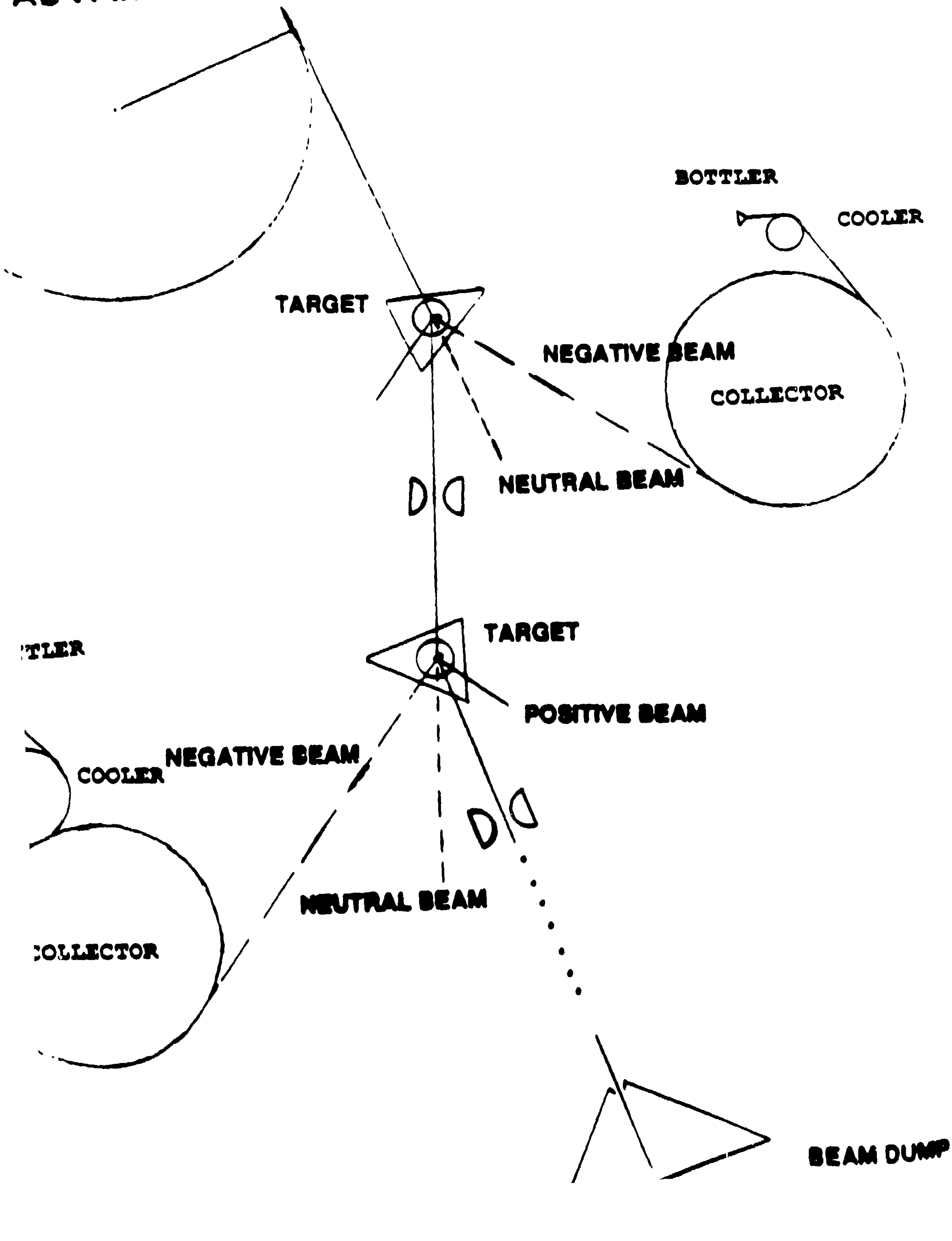
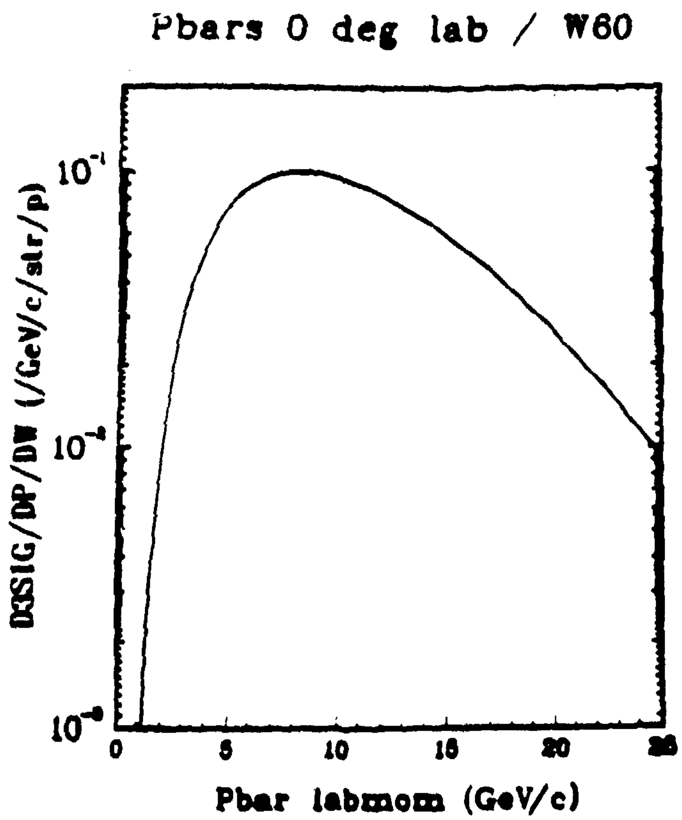
HQ
HQ
HQ
HQ
HQ
HQ
BH
Target Wheel (W)
0 m 1

(b)

ADVANCED HADRON FACILITY

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Pbar labmom (GeV/c)
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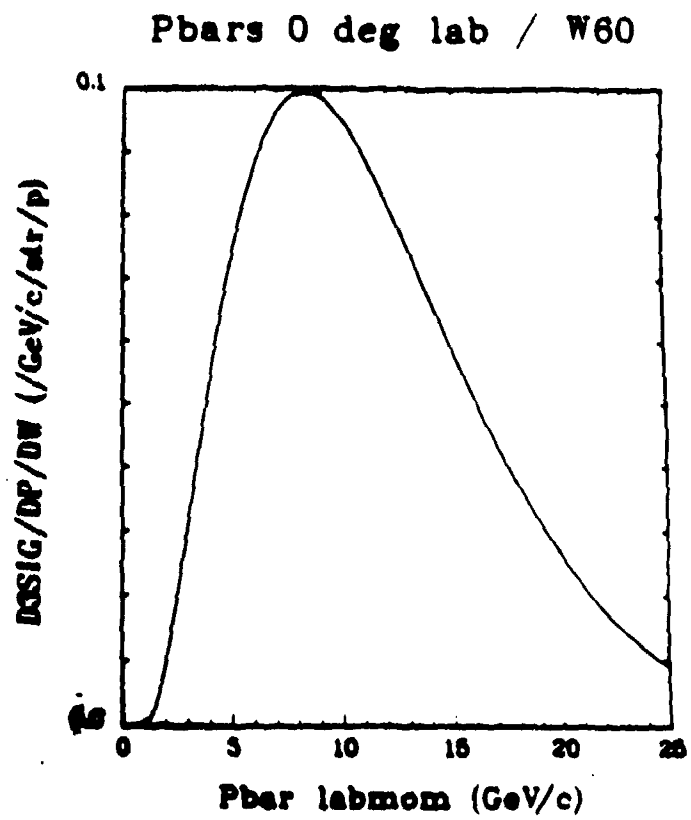
10
15
20
25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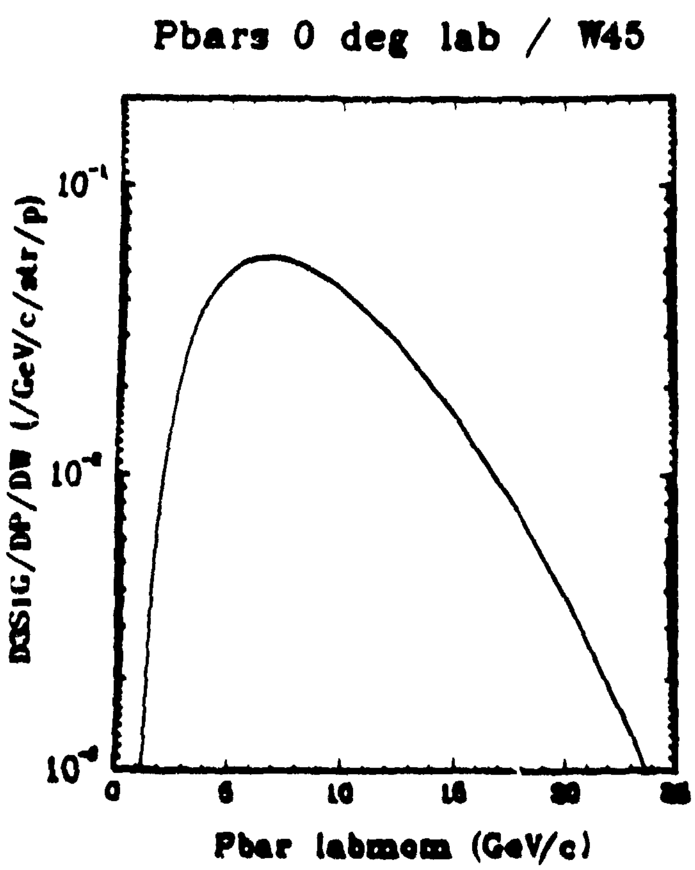
25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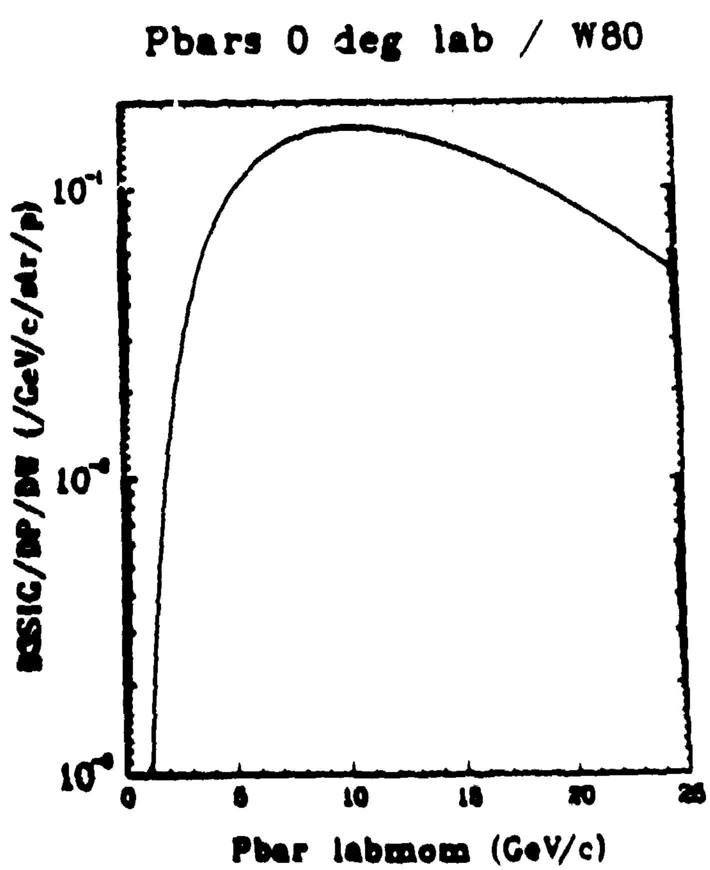
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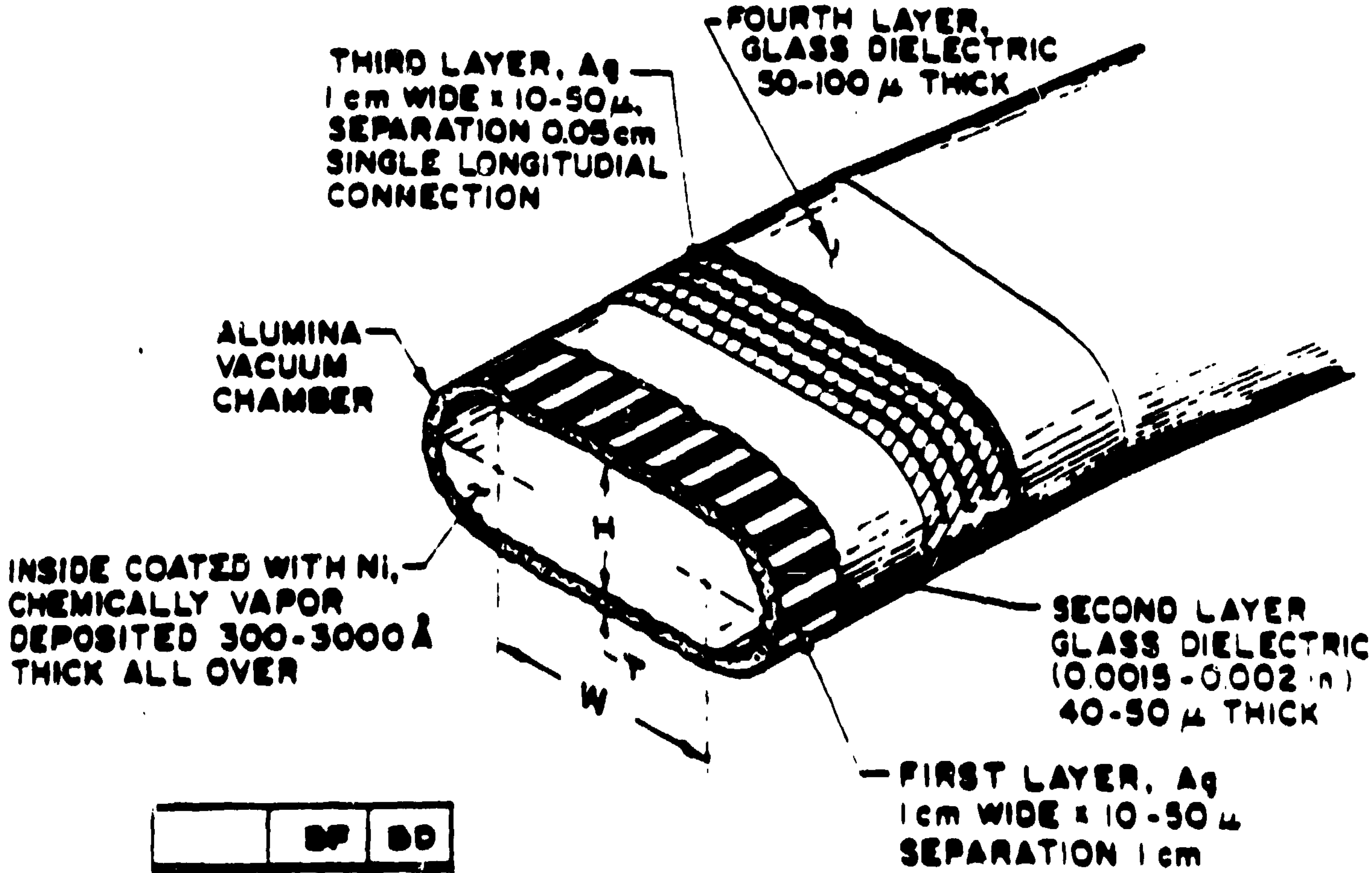

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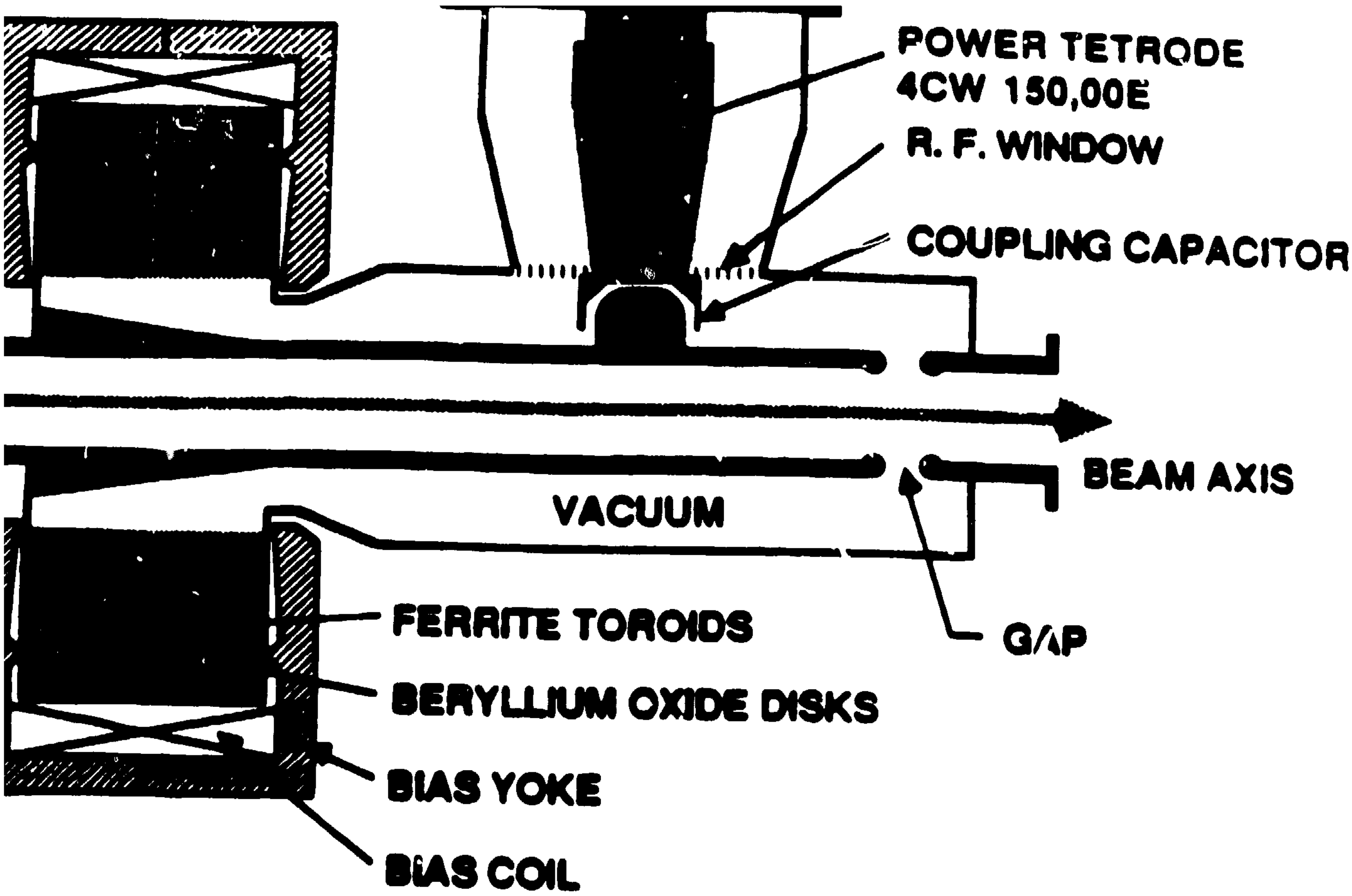
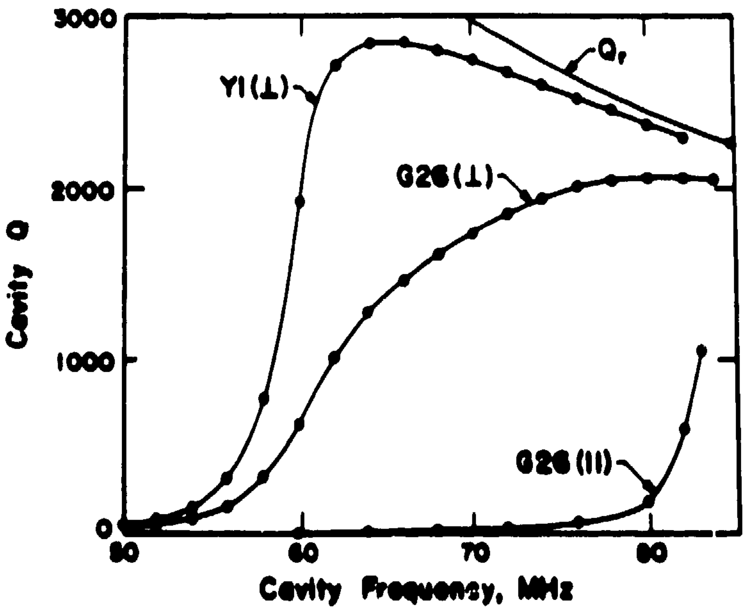
H	4.5	7
W	13	7
T	0.5	0.3

ALL CM.


POWER TETRODE
4CW 150,00E
R. F. WINDOW
COUPLING CAPACITOR
BEAM AXIS
VACUUM
GAP
FERRITE TOROIDS
BERYLLIUM OXIDE DISKS
BIAS YOKE
BIAS COIL



3000
2000
1000
0
50
60
70
80
Cavity Q
Cavity Frequency, MHz
Y1(⊥)
G26(⊥)
G26(||)